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THE SYNOPTIC *SWIFT* SYNERGY—CATCHING GAMMA-RAY BURSTS BEFORE THEY FLY

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ABSTRACT

The advent of large panoramic photometric surveys of the sky offers the possibly of exploring the association of gamma-ray bursts (GRBs) with supernovae. To date, a few GRBs have been connected possibly with supernovae: GRB 980425–SN 1998bw, GRB 011121–SN 2001ke, GRB 970228, and GRB 980326. A combination of a large detection rate of GRBs and rapid coverage of a large portion of the sky to faint magnitude limits offers the possibility of detecting a supernova preceding an associated GRB or at least placing limits on the rate of association between these two phenomena and the time delay between them. This would provide important constraints on theoretical models for GRBs.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The gamma-ray burst GRB 021004 was detected by *HETE-2* at 12:06 UT on 2002 October 4 (Shirasaki et al. 2002). Observations after about 9 minutes from the trigger revealed a fading optical transient (Fox 2002), which was densely sampled in several bands, especially at early times. The afterglow of GRB 021004 has shown several unusual features (Mirabal et al. 2002; Salamanca et al. 2002; Möller et al. 2002; Bersier et al. 2003). Perhaps its most unique feature was that the field had been observed shortly before the gamma-ray burst (GRB) itself was detected. Wood-Vasey et al. (2002) give a limiting unfiltered magnitude of 21.4 for observations on the day before the burst and 22.3 integrated over the year before the burst.

Astronomy is on the threshold of a new era in which large portions of the sky are surveyed deeply and regularly. The question arises, what is likelihood of getting photometry of a GRB precursor, specifically if supernovae precede GRBs as in the supranova model (Vietri & Stella 1998)? Although the flux upper limits for GRB 021004 are not stringent enough to constrain theoretical models of GRBs, the high burst localization rate of *Swift* combined with the fast sky coverage of the Sloan Digital Sky Survey (SDSS) and later Pan-STARRS, the Large Synoptic Survey Telescope (LSST), and the *Supernova/Acceleration Probe* (*SNAP*) could provide important constraints on GRB precursors.

During the first and second years of operation of the *Swift* mission, SDSS will scan approximately 3000 square degrees (or 7% of the sky) each year (SDSS Collaboration 2001). Over this area it will detect point sources down to $R \approx 23.2$. If *Swift* or subsequent missions are operational in 2006, the Pan-STARRS program will observe 20,000 square degrees every 4 days (or 50% of the sky) to a limiting magnitude of $R \approx 24.2$ (Kaiser et al. 2002). Finally, potentially beginning in 2010, *SNAP* will cover 15 square degrees every 4 days, with each observation reaching a limiting magnitude of $R \approx 28$ (Kim et al. 2002); co-adding observations over a month would go 1 mag deeper. The *SNAP* lensing survey will cover 300 square degrees over 5 months to a similar limiting magnitude.

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Long gamma-ray bursts are thought to be associated with the collapse of a massive star, a supernova. Specifically, in the collapsar model, the formation of a black hole in the center of the star results in relativistic jets that pierce the envelope of the star (MacFadyen & Woosley 1999). Along the axis of the jets, the collapsing star appears as a gamma-ray burst, and the supernova reaches its peak a few weeks after the GRB. Vietri & Stella (1998) proposed an alternative model in which the gamma-ray burst accompanies the delayed collapse of a quickly spinning neutron star that is more massive than the maximum mass of a nonrotating neutron star. The neutron star may take several months or years after the supernova to spin down to the critical frequency and collapse.

In this paper, I estimate the number of GRB events with photometry that overlap on the sky but shortly precede in epoch from SDSS and other surveys and compare the flux limits with the expected flux from a supernova that may precede the GRB.

2. GAMMA-RAY BURST OVERLAP WITH FUTURE SURVEYS

To calculate how often sufficiently deep photometry will precede the observation of a GRB on the sky, several ingredients are required: a model for the spectral energy distribution as a function of time of a supernova associated with a GRB, an estimate of the luminosity-rate function of GRBs as a function of redshift [$\dot\phi(z, L)$], a model for the field of view of the gamma-ray burst detector ($\Omega_{\rm GRB} = 2$ for *Swift*) and its detection threshold (P_1), and the rate of sky coverage of the photometric program ($\mathscr{R}_{\rm photo}$) and its detection threshold ($R_{\rm lim}$). Porciani & Madau (2001) provide models for $\dot\phi(z, L) \equiv R_{\rm GRB}(z)\psi(L)$. The rate of GRBs, $R_{\rm GRB}(z)$, is taken to be proportional to the star formation rate, and the luminosity function of GRBs, $\psi(L)$, is constrained by the BATSE GRB number counts. The rate of overlapping photometry is given by the product of the rate of sky coverage with an integral over the assumed cosmological distribution of GRBs,

$$\frac{dN_{\rm overlap}}{dt}(P > P_1, R < R_{\rm lim}) = \frac{\mathscr{R}_{\rm photo}\Delta t}{4\pi}\frac{dN_{\rm total}}{dt}(P > P_1, R < R_{\rm lim}) , \quad (1)$$

$$\frac{dN_{\rm total}}{dt}(P > P_1, R < R_{\rm lim}) = \frac{\Omega_{\rm GRB}}{4\pi}\int_0^{z:R(z)=R_{\rm lim}} dz \int_{L(P_1,z)}^{\infty} dL \frac{dV(z)}{dz}\frac{\dot{\phi}(z,L)}{1+z} \ . \quad (2)$$

For lack of a better model for the evolution of a supernova associated with a GRB, I assume that SN 2001ke (Garnavich et al. 2003) is a prototype for this class, and furthermore that a supernova associated with a GRB maintains its peak brightness for a period $\Delta t = 14(1+z)$ days in the observer's frame and otherwise is undetectable (see Reichart 1999 and Bloom et al. 1999 for other GRB-associated supernovae). It is reasonable to use the median value of z for GRBs whose associated supernovae are brighter than the magnitude limit of the particular photometric survey. However, to be highly conservative, I take $\Delta t = 14$ days to calculate the rate of overlap.

If a survey covers the same area of sky more often than once per interval Δt, as does the *SNAP* supernovae search and Pan-STARRS, the rate of sky coverage $\mathscr{R}_{\rm photo}$ should only account for the first visit in each period Δt; for example, $\mathscr{R}_{\rm photo}$ for Pan-STARRS is 2π per 14 days. The additional visits during each fortnight do not increase $\mathscr{R}_{\rm photo}$, but they do allow the survey to probe deeper by co-adding the successive images.

According to the original supranova model (Vietri & Stella 1998), the supernova may reach its peak at any time up to several years before the GRB, so this calculation implicitly assumes that both the GRB survey and the photometric survey will be operating at the appropriate times. Here $L(P_1, z)$ is the luminosity of a GRB at a redshift z that is detected at a count rate of P_1, and $R(z)$ is the R-band apparent magnitude of a GRB-associated supernova at a redshift z. Both of these functions include the k-correction (Hogg 1999) and assume the cosmographic parameters $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. Figure 1 shows the number per year of GRBs detected by *Swift* whose associated supernova would be brighter at its peak than a particular R-band magnitude.

The results shown in Figure 1 assume the SF1 model of Porciani & Madau (2001). This model provides a conservative lower limit for the overlap. It predicts that *Swift* will localize about 110 bursts per year—the more generous estimates range up to 300 bursts per year (Myers 2002).[3] Furthermore, this model predicts that the bursts detected will be at higher redshifts than other models, so the accompanying supernovae will be fainter and more difficult to detect.

Table 1 gives the overlap rate between various photometric surveys and the *Swift* GRB localization mission. What is striking is that the shallow but wide Pan-STARRS and LSST surveys will perform much better than any of the other surveys. Furthermore, if supernovae precede GRBs, Pan-STARRS and LSST each should detect nearly 10 GRB-associated supernovae per year. If they find none, it would place severe constraints on the supranova model for GRBs. It must be emphasized that this rate of overlap is extremely conservative. It assumes a low *Swift* burst localization rate and a distribution of GRBs skewed to high redshift (therefore, faint associated supernovae). The actual rate of overlap will probably be higher if both programs operate simultaneously. Furthermore, *Swift* will generate a catalog of burst positions and redshifts. One should be able to cross-correlate a posteriori this catalog with earlier Pan-STARRS or LSST observations and exclude the appearance of transients to $R \approx 25$ over a wide range of epochs preceding the burst yielding definitive constraints on GRB progenitors independent of assumptions about the GRB luminosity function and its evolution.

[3] See http://swift.gsfc.nasa.gov.

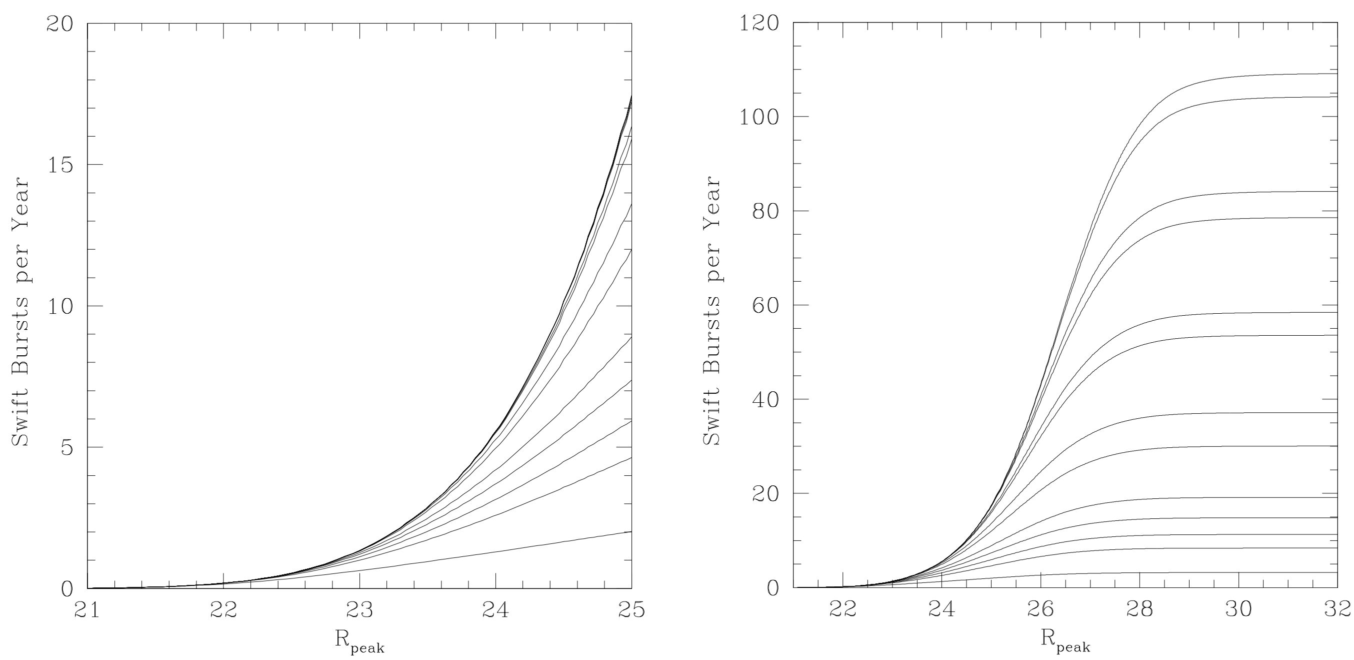

Fig. 1.—Number of GRB-associated supernovae brighter than a given R-magnitude. The lines show the cumulative contribution of GRBs above given flux limits. The right panel shows the entire distribution, while the left panel focuses on the bright end. From bottom to top, only the supernovae associated with GRBs whose peak flux is above $10^{0.9}$, $10^{0.6}$, $10^{0.5}$, $10^{0.4}$, $10^{0.3}$, $10^{0.1}$, 1, $10^{0.2}$, $10^{-0.25}$, $10^{-0.45}$, $10^{-0.5}$, $10^{-0.7}$, and $10^{-0.75}$ photons cm^{-2} s^{-1}. See Porciani & Madau (2001) for further details.

TABLE 1
PRESENT AND FUTURE LARGE-SCALE PHOTOMETRIC SURVEYS

Survey	$R_{\rm lim}$	$z_{\rm max}$	$z_{\rm med}$	$\mathscr{R}_{\rm photo}\Delta t$	$dN_{\rm total}/dt$ (yr^{-1})	$dN_{\rm overlap}/dt$ (yr^{-1})
SDSS	23.2	0.56	0.48	0.035	1.9	0.0052
Pan-STARSS (single)	24.2	0.78	0.66	6.3	7.1	3.6
Pan-STARSS (co-added)	25.0	1.00	0.83	6.3	17.0	8.8
LSST (single)	24.5	0.86	0.72	6.3	10.0	5.1
LSST (co-added)	25.1	1.04	0.85	6.3	19.0	9.8
SNAP SN (single)	28.0	2.59	1.45	0.0046	98.0	0.036
SNAP SN (co-added)	28.8	3.35	1.50	0.0046	110.0	0.039
SNAP lensing	28.0	2.59	1.45	0.0091	98.0	0.071

This calculation of the overlap rate assumes that either the GRB localization program or the photometric survey studies random portions of the sky. In fact, both the *Swift* mission and all of the photometric surveys avoid studying the region of the sky near the Sun. Although the average rate of overlap over a year in given by the formulae above and the values in the tables, the chance of detecting the supernova associated with GRB is somewhat higher than average if the supernova precedes the GRB by less than 3 months or between 9 and 15 months. If the supernova precedes the GRB by 6–9 months, the chance of detecting it is somewhat lower than average. However, this seasonal variation is smaller than the uncertainties in the GRB luminosity function.

3. DISCUSSION

The philosophy employed for finding GRB precursors is somewhat different than what is necessary for finding supernovae or microlensing events. Because the precursors will be sought after the GRB is detected and localized, it is not necessary to have more than one epoch of data from the particular region of sky before the burst. Even a single epoch would yield important constraints. Furthermore, unless the cadence of the observations is sufficiently low (no more than biweekly), the repeated observations of the same patch of sky do not improve the chances of catching a precursor (unless one co-adds the data to probe deeper), because supernovae typically evolve over the course of weeks. Consequently, although supernova and microlensing surveys have a large data rate of high-quality photometry, because of their relative lack of sky coverage and depth they do not contribute much to the detection rate of precursors. From another point of view, only a small fraction ($<10^{-4}$) of supernovae result in GRBs directed toward us, so one would typically have to find at least $10^4(4\pi/\Omega_{\rm GRB})$ supernovae in a blind search before finding a single GRB-associated supernova.

The best bets are the large, deep, wide surveys of the sky. SDSS is the prototype, and Pan-STARRS and LSST should deliver results. There is a small possibility that SDSS will catch a supernova before a GRB, providing important evidence for the supranova model for GRBs (it may have done so already). Pan-STARRS or LSST, if it overlaps with a high localization rate GRB mission such as *Swift*, will be able to provide important constraints on GRB models. Specifically, it should be able to exclude the possibility that GRBs follow supernovae within a year.

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REFERENCES

Bersier, D., et al. 2003, ApJ, 584, L43
Bloom, J. S., et al. 1999, Nature, 401, 453
Fox, D. 2002, GCN Circ. 1564 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1564.gcn3)
Garnavich, P. M., et al. 2003, ApJ, 582, 924
Hogg, D. 1999, preprint (astro-ph/9905116)
Kaiser, N., et al. 2002, POI: The Panoramic Optical Imager (Institute for Astronomy Tech. Rep.)
Kim, A., et al. 2002, Lawrence Berkeley Laboratory Tech. Rep. LBNL-51151
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Mirabal, N., Armstrong, E. K., Halpern, J. P., & Kemp, J. 2002, GCN Circ. 1602 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1602.gcn3)
Möller, P., et al. 2002, A&A, 396, L21
Myers, J. D. 2002, *Swift*: Catching Gamma-Ray Bursts on the Fly (NASA Tech. Rep.)
Porciani, C., & Madau, P. 2001, ApJ, 548, 522
Reichart, D. E. 1999, ApJ, 521, L111
Salamanca, I., Rol, E., Wijers, R., Ellison, S., Kaper, L., & Tanvir, N. 2002, GCN Circ. 1611 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1611.gcn3)
SDSS Collaboration. 2001, Five-Year Baseline Plan for SDSS Operations (Sloan Digital Sky Survey Tech. Rep.)
Shirasaki, Y., et al. 2002, GCN Circ. 1565 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1565.gcn3))
Vietri, M., & Stella, L. 1998, ApJ, 507, L45
Wood-Vasey, W. M., Aldering, G., Lee, B. C., Helin, E. F., Pravdo, S., Hicks, M., & Lawrence, K. 2002, GCN Circ. 1572 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1572.gcn3)